

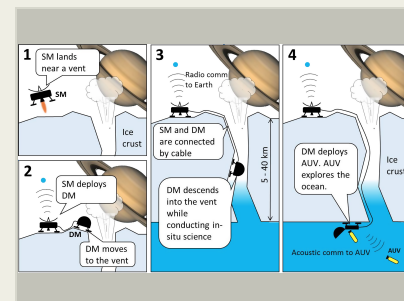
Journey to the Center of Icy Moons

Completed Technology Project (2016 - 2017)



Project Introduction

In Jules Verne's classic science fiction, *Journey to the Center of the Earth*, Professor Otto Lidenbrock and his company descend into an Icelandic volcano to explore it in the name of science, discover a vast subterranean ocean among other unexpected wonders, and must resiliently survive the experience to complete their mission. This is exactly what we want to do in reality on Europa and Enceladus. Several concepts have already been studied to explore these moons' subsurface oceans using autonomous underwater vehicles (AUVs). However, access to subsurface ocean remains to be an outstanding challenge. The proposed concept is to deploy a surface-to-subsurface robotic system, namely Icy-moon Cryovolcano Explorer (ICE), which will land on the surface of an icy moon, traverse to a cryovolcano, descend into its opening, perform in-situ science in the vent or crevasse, and ultimately deploy underwater vehicles to explore a subsurface ocean. ##ICE involves three modules: Descent Module (DM), Surface Module (SM), and AUVs. DM carries AUVs and descends into a vent by using a combination of roving, climbing, rappelling, and hopping, like an experienced human alpinist. The estimated gas density of an ejecting plume is sufficiently low, therefore its dynamic pressure (< 1 Pa) would not be an obstacle for descent. SM stays on the surface, generates power by RTG and/or solar cells, and communicates with Earth. DM relies on the power and communication link provided by SM through a cable to minimize the size and weight. It is a highly autonomous agent being capable of quickly responding to a dynamically changing environment, such as episodic eruption, and resiliently handling any anomalies under significant communication latency. Once DM reaches the subsurface ocean, it launches the AUVs to explore the exotic environment that potentially harbors life. ##ICE brings three unique benefits. First, it enables in-situ science in a cryovolcano vent. Although orbiters can perform in-situ science of plumes, relatively large (up to $1\ \mu\text{m}$) dust grains are hard to reach orbital altitude. Yet it is those mineral grains that carry rich information about the habitability of the subsurface ocean. Second, ICE enables the exploration of subsurface oceans by providing an access to it. Third, it enables the operation of AUVs in subsurface ocean by providing three essential services: communication, localization, and power. Since water blocks radio waves, communication and localization are particularly significant challenges for AUVs. DM of ICE communicates with AUVs through acoustic communication. DM then transfers the data through an optic cable to SM, from which the data is transmitted to Earth by radio. DM also sends an acoustic localization beacon and serves as a battery charging station, potentially unnecessitating RTG on the AUV. ##In the proposed study we will (1) develop mission concepts for ICE, (2) identify the primary risks associated with the mission, and identify potential mitigations for these risks, and (3) perform a feasibility analysis for the mission, which will include performing several system trades, including one focused on the hardware platform (e.g., climbing robot vs. repelling robot vs. hovering robot), and another one focused on the autonomy software capabilities (with the goal to identify the appropriate scope of the autonomous functionality required to



cy-moon Cryovolcano Explorer (ICE) consists of three modules: Descent Module (DM), Surface Module (SM), and autonomous underwater vehicles (AUVs). DM descends into a vent by using a combination of roving, climbing, rappelling, and hopping, while...

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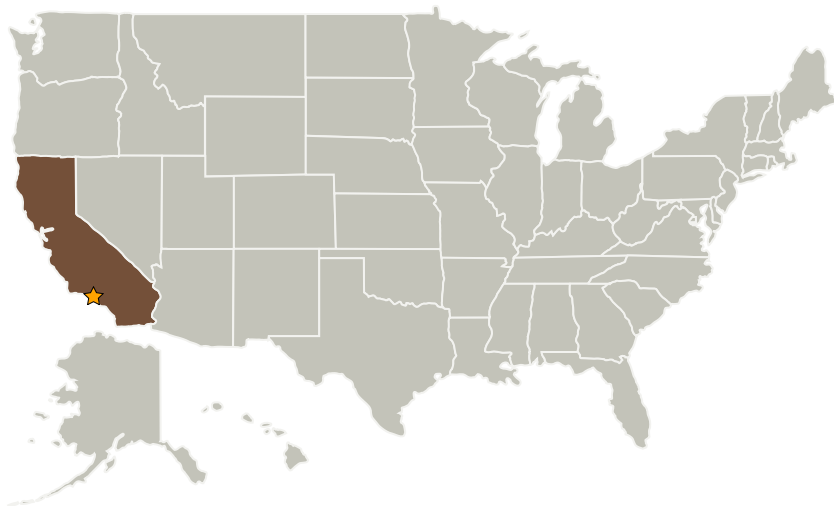


execute the mission concepts). These tasks will result in identifying driving requirements for the system, including candidate science targets, power needs, resilience needs, etc. In summary, we will develop a concept for ICE that elaborates and refines the science and exploration benefits described above, and we will analyze the benefits and risks associated with realizing this concept. A successful completion of the project will mature this exciting concept into a credible element of the growing outer planets and icy moons exploration portfolio.

Anticipated Benefits

The Icy-moon Cryovolcano Explorer (ICE) brings three unique benefits. First, it enables in-situ science in a cryovolcano vent. Although orbiters can perform in-situ science of plumes, relatively large (up to 1 μm) dust grains are hard to reach orbital altitude. Yet it is those mineral grains that carry rich information about the habitability of the subsurface ocean. Second, ICE enables the exploration of subsurface oceans by providing an access to it. Third, it enables the operation of AUVs in subsurface ocean by providing three essential services: communication, localization, and power. Since water blocks radio waves, communication and localization are particularly significant challenges for AUVs. DM of ICE communicates with AUVs through acoustic communication. DM then transfers the data through an optic cable to SM, from which the data is transmitted to Earth by radio. DM also sends an acoustic localization beacon and serves as a battery charging station, potentially unnecessitating RTG on the AUV.

Primary U.S. Work Locations and Key Partners



Organizational Responsibility

Responsible Mission Directorate:

Space Technology Mission Directorate (STMD)

Lead Center / Facility:

Jet Propulsion Laboratory (JPL)

Responsible Program:

NASA Innovative Advanced Concepts

Project Management

Program Director:

Jason E Derleth

Program Manager:

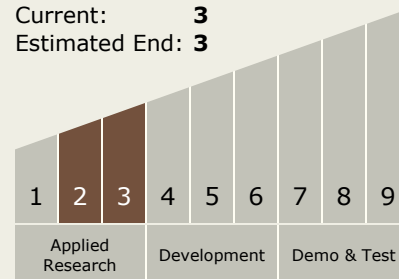
Eric A Eberly

Principal Investigator:

Masahiro Ono

Technology Maturity (TRL)

Start: 2
Current: 3
Estimated End: 3



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Organizations Performing Work	Role	Type	Location
★ Jet Propulsion Laboratory(JPL)	Lead Organization	NASA Center	Pasadena, California
Massachusetts Institute of Technology(MIT)	Supporting Organization	Academia	Cambridge, Massachusetts
Università di Pisa	Supporting Organization	Academia	Pisa, Outside the United States, Italy

Primary U.S. Work Locations

California

Project Transitions

 **July 2016:** Project Start

Technology Areas

Primary:

- TX04 Robotic Systems
 - └ TX04.2 Mobility
 - └ TX04.2.1 Below-Surface Mobility

Target Destination

Others Inside the Solar System

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June 2017: Closed out

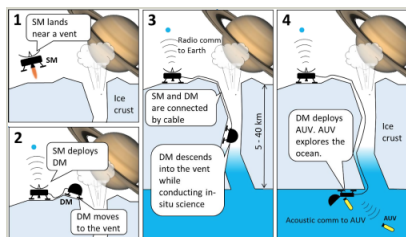
Closeout Summary: Sometimes Nature acts as if it is waiting to be explored. For example, it secretly installed doors on the icy shell of Enceladus - vents through which water vapor and other materials are ejected from the subsurface ocean into outer space. The doors may serve as a natural pathway through the ice crust, which is tens of kilometers thick, to reach the extraterrestrial ocean. The doors may provide us with an opportunity to investigate a unique environment in the vent-conduit systems, which themselves could be habitable. The doors may lead us to the discovery of the second origin of life. The doors may lead us to the answer to mankind's ultimate question - are we alone? The doors are just 10 AUs away from us. Why would we leave them open and unexplored? Our concept, Enceladus Vent Explorer (EVE), is a robotic pathfinder mission to enter these doors. EVE's goals are to descend into erupting conduits up to ~2km deep, characterize the unknown interior structure of the vent-conduit system, assess the accessibility to the subsurface ocean through the vent-conduit system, potentially reach the liquid interface, and perform astrobiology and volcanology observations in the vent-conduit system. EVE sends two types of modules: Surface Module (SM) and Descent Module (DM). SM is a lander that stays on the surface, while tens of small (~3 kg, 10 cm in width and 30 cm in length) DMs separate from SM, move to a vent, and descend into it. DMs rely on a power and communication link provided by SM through a cable. As the payload volume of DM is extremely limited, each DM can carry only a single miniaturized instrument. This limitation is complemented by heterogeneity. There are several types of DMs, all of which share the common mobility system but carry different instruments. For example, a scout DM creates a 3-D map of the geyser system with its stereo cameras and structured light. A sample return DM collects particles and ice cores in the vent and deliver them to the mass spectrometer in the SM. An in-situ science DM carries science instruments, such as a microscopic imager and a microfluidics chip for biosignature detection. DMs are sent either sequentially or in parallel. The two greatest difficulties for EVE are the uncertainty in i) the dynamic pressure due to the upward flow and ii) the size of vent. Despite remote observations by the Cassini spacecraft, these two parameters remain poorly characterized. Among the numerous unknowns associated with Enceladus vents, the one that has the greatest impact on the two key parameters is the eruption mechanism. Most hypothetical eruption models that have been proposed thus far fall into either of two categories, which we refer to as the relatively calm boiling models, and the more dynamic cryovolcanic models. Very roughly speaking, the boiling models assume that liquid water boils into vapor under the surface, while the cryovolcanic models assume that a fairly pure form of the ocean material ascends the conduit driven by exsolution and expansion of dissolved materials and phase changes. More detailed explanations of the two models will be provided shortly. Existing Cassini observations cannot resolve between the two models. The boiling models are more favorable for EVE because they result in a greater vent size and lower dynamic pressure. The worst-case dynamic pressure is ~104 Pa, which is well within the design range of DM. While the vent size is harder to constrain, the boiling models give order-of-magnitude greater estimates than the cryovolcanic model in general. For example, Kite and Rubin [2016] suggest slots of greater than 1-m in width. Therefore, EVE is likely feasible assuming the boiling models. The cryovolcanic models are more problematic for EVE. Our preliminary analysis suggests that the dynamic pressure and the vent width could be anywhere between 103 - 107 Pa and 1-30 cm, respectively. The worst-case dynamic pressure is beyond the upper limit for DM. While some work suggests 107 Pa dynamic pressure is likely unreasonable for geophysical reasons (D. Hemingway, pers. comm.) and more detailed analysis could better constrain the worst cases, we do not reject these possibilities. Therefore, the feasibility of EVE is undetermined with the current best knowledge under the cryovolcanic models. Further study of Cassini data could better constrain parameter estimates of each model. In order to resolve between boiling and cryovolcanic models, additional orbital observations are likely needed. While observations from orbit around Enceladus could help provide some insight into the appropriate model, uncertainties in interior geometries and vertical profiles of dynamic pressure cannot be significantly reduced without descending into the vent. Therefore, the first mission into an Enceladus vent must face a chicken-and-egg problem: dynamic pressure and vent size remain uncertain until it descends into the vent, but designing a robot to descend into the vent requires knowledge of those parameters. Consequently, in order to maximize the chance of mission success, EVE's DM needs to be designed conservatively in terms of size and resistance to dynamic pressure. Our trade study has determined that the DM configuration that is most robust to the uncertainties in vent parameters is a limbed robot with ice screws as the end effector. An anchoring mechanism is needed because the upward force exerted by the jet is orders of magnitude greater than the downward force exerted by Enceladus's weak gravity (~0.01g). An ice screw is a hollow metal screw used by alpinists for ice climbing. As a byproduct, it produces an ice core when screwed in, which could be brought back by the sample return DMs. Since an ice screw can make a strong anchor with only one wall (as opposed to wedging, for example, which requires two walls), it is robust to uncertainty in the width of conduit. We validated by ice chamber experiments that ice screw end effectors can tolerate the force exerted by ~105 Pa dynamic pressure on the DM. Our trade study also concluded that the most realistic way to power DM is to provide power from SM through a cable because neither RTGs nor primary batteries that fit in the limited volume of DM can provide sufficient energy for the mobility system within a reasonable mission duration. A cable also elimi

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Images



Project Image

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Links

NASA.gov Feature Article
(<https://www.nasa.gov/feature/journey-to-the-center-of-icy-moons>)